Fuel Processors for PEM Fuel Cells

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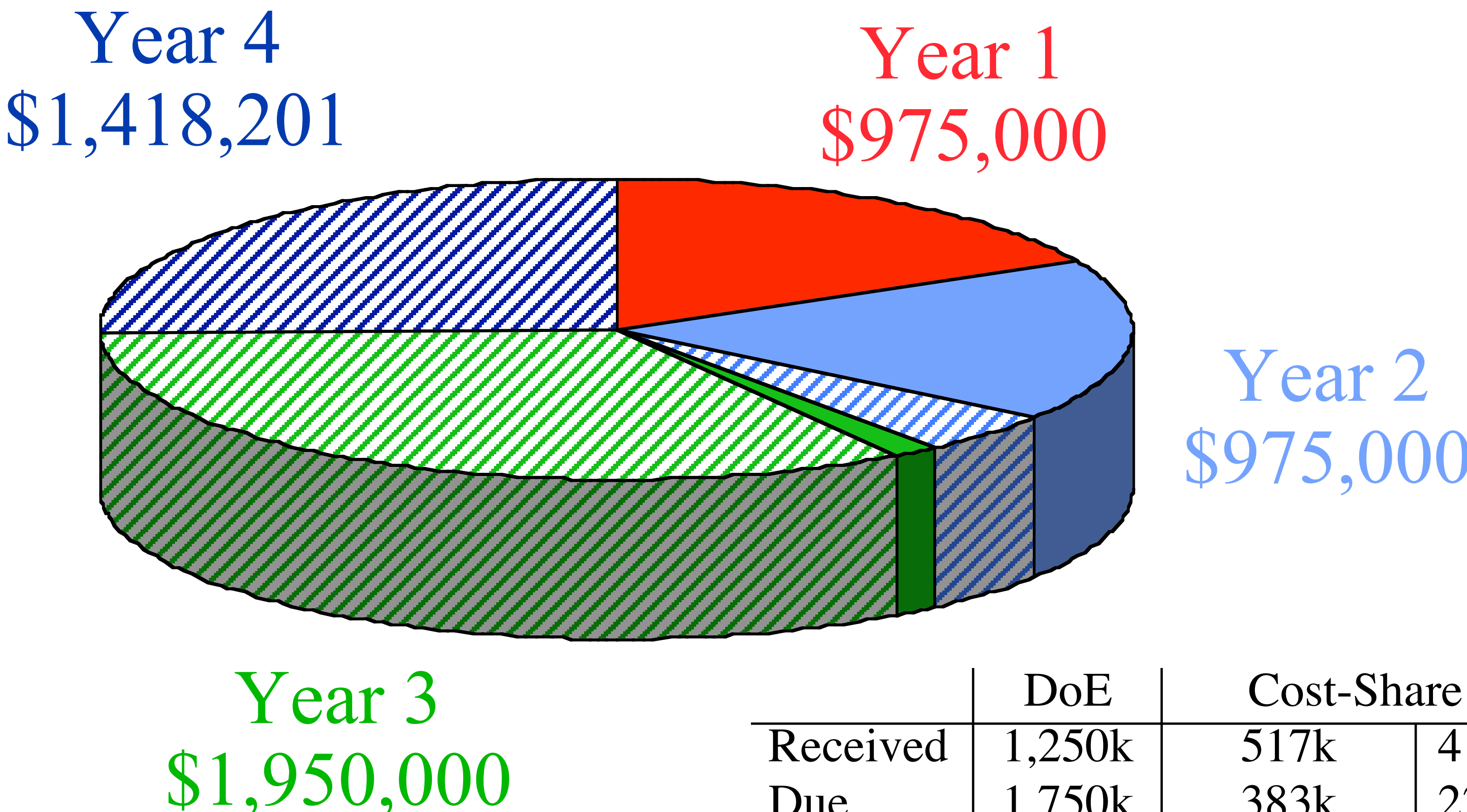
Project Objectives

- Develop high performance, low-cost materials
  - High capacity sulfur adsorbents for liquid fuels
  - High activity and durable Autothermal Reforming (ATR), Water Gas Shift (WGS) and Preferential Oxidation (PrOx) catalysts
- Design and demonstrate microreactors employing high performance catalysts
- Design and demonstrate microvaporizer/combustor
- Design and demonstrate thermally integrated microsystem-based fuel processors
- Evaluate system cost

Total Budget (as of March, 2004)



	DoE	Cost-Share	
Received	1,250k	517k	41%
Due	1,750k	383k	22%

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Fuel Processor (Fuel Cell) Technical Barriers

- Fuel Processor Startup/Transient Operation
  - Improved catalysts, sorbents and reactors
  - Thermal integration
  - Decreased unit operations
- Durability
  - Improved impurity tolerance
  - Improved resistance to coking and sintering
- Emissions and Environmental Issues
- Hydrogen Purification/CO Cleanup
  - Improved catalysts, sorbents and reactors
- Fuel Processor System Integration and Efficiency
- Cost
  - Improved catalysts, sorbents and reactors
  - Integration and decreased unit operations

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Fuel Processor (Fuel Cell) Technical Targets

Characteristics	Units	Current Status (2003)	Target for Year: 2005	Target for Year: 2010
Energy efficiency	%	78	78	80
Power density	W/L	700	700	800
Specific power	W/kg	600	700	800
Cost	$/kWe	65	25	10
Cold startup time to max power @ -20 °C ambient temperature @ +20 °C ambient temperature	 min min	 TBD <10	 2.0 <1	 1.0 <0.5
Transient response (10% to 90% power)	sec	15	5	1
Emissions		<Tier 2 Bin 5	<Tier 2 Bin 5	<Tier 2 Bin 5
Durability	hours	2000	4000	5000
Survivability	°C	TBD	-30	-40
CO content in product stream Steady state Transient	 ppm ppm	 10 100	 10 100	 10 100
H_2S content in product stream	ppb	<200	<50	<10
NH_3 content in product stream	ppm	<10	<0.5	<0.1

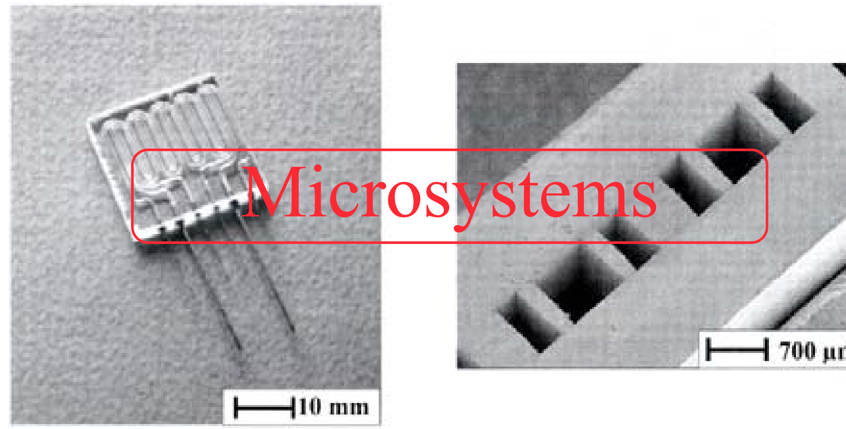
Approach

High Performance Materials

+

High Degree of Integration

+



Project Director:	Levi Thompson (ltt@umich.edu)
Co-PIs:	Gulari, Savage, Schwank & Yang (ChE); Assanis, Im, Ni & Wooldridge (ME); Dahm & Powell (Aero)
Subcontractors:	Ricardo, Inc. (MI); Osram Sylvania; IMM (Germany); MesoFuel (NM)

Project Safety

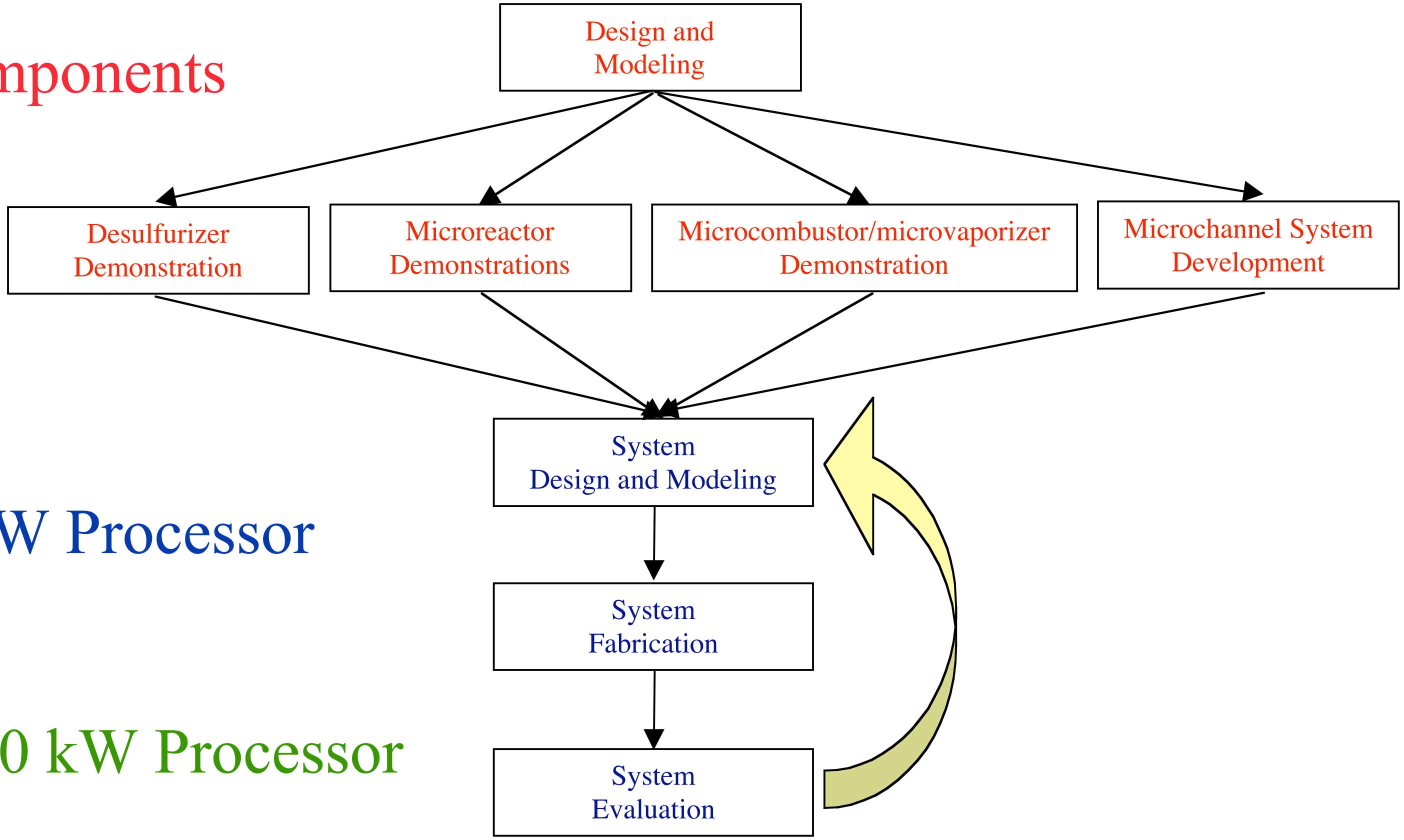
- Preliminary Identification of Safety Vulnerabilities (e.g. FMEA, HAZOP)
- System Safety Assessment
- Risk Mitigation Plan
- Safety Performance Assessment
- Communications Plan

Project Timeline

Phase I: Components

Phase II: 1 kW Processor

Phase III: ≤10 kW Processor

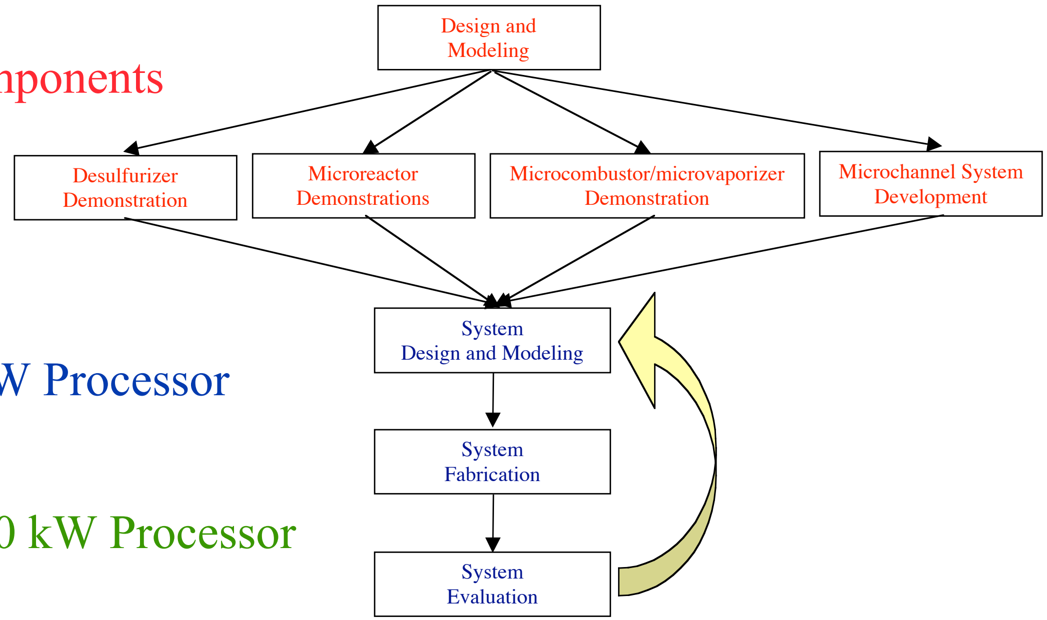


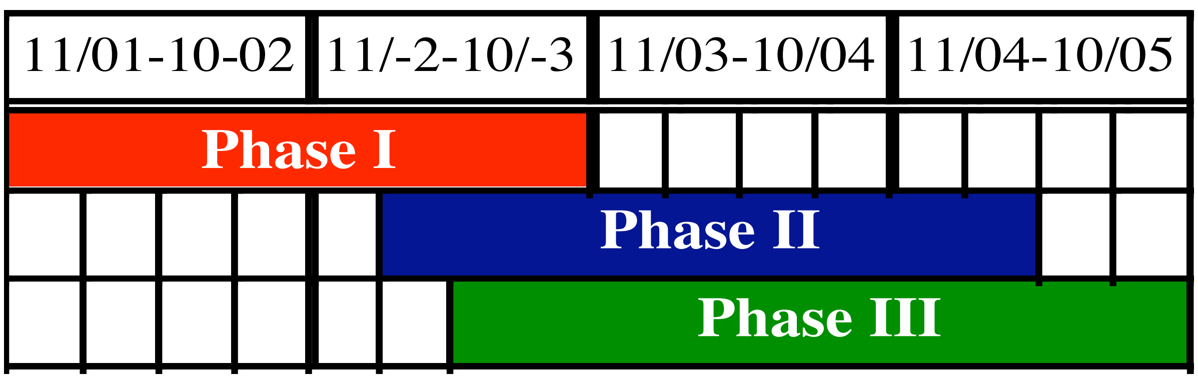
Project Timeline

Phase I: Components

Phase II: 1 kW Processor

Phase III: ≤10 kW Processor





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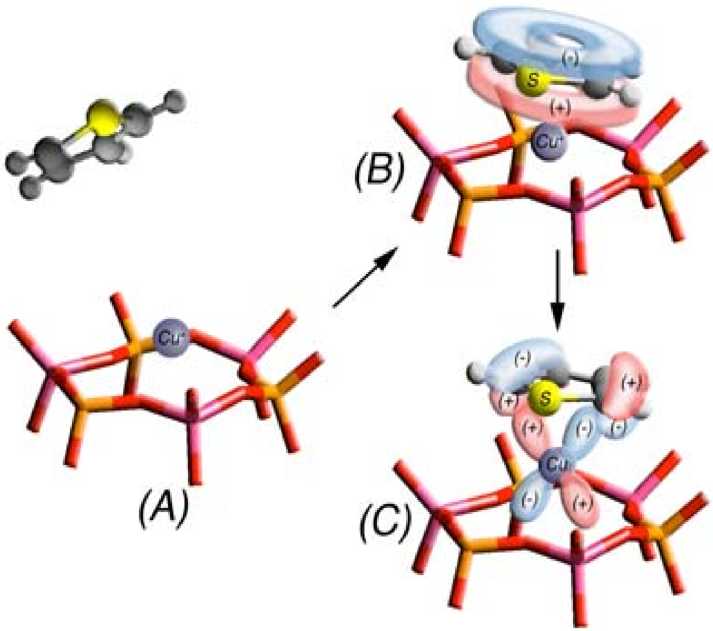
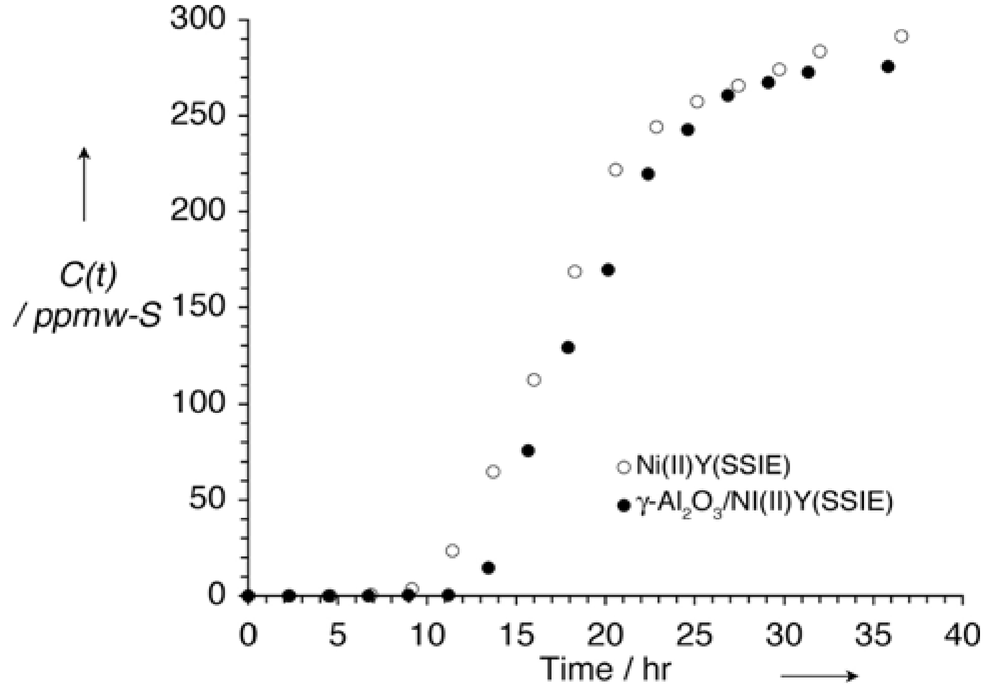
Desulfurization of Fuels by Adsorption

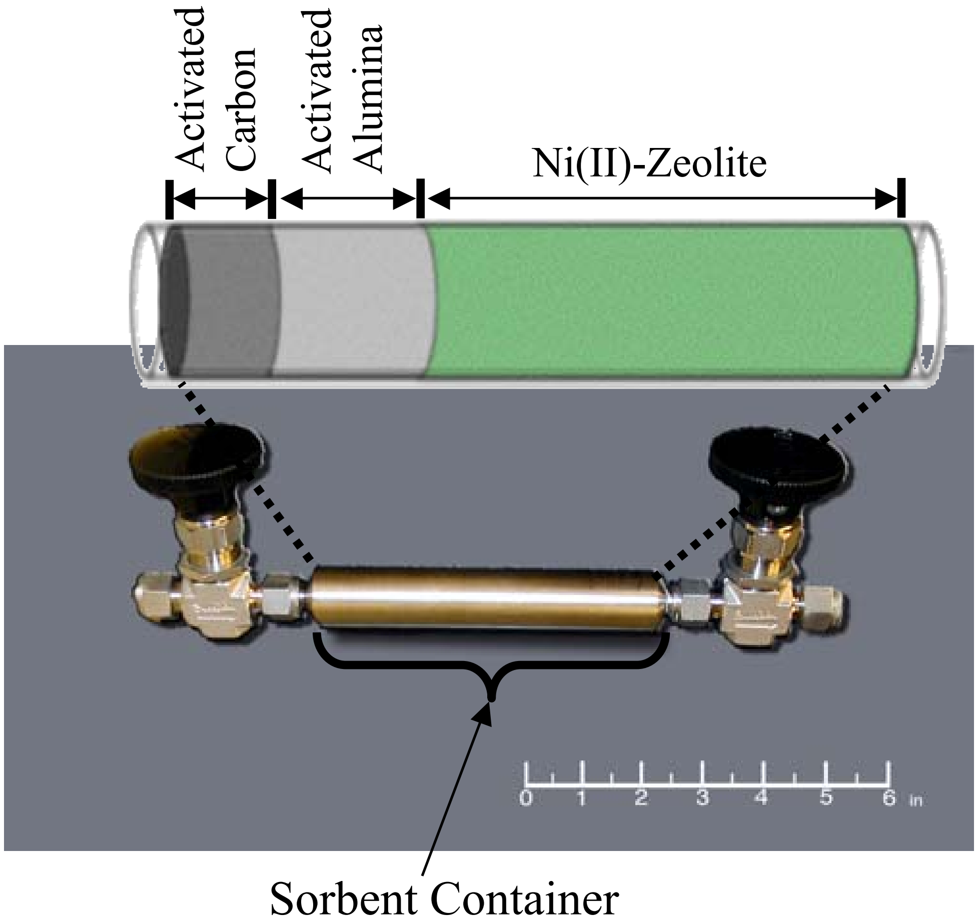




π-Complexation Mechanism:

- Cu ions occupy faujasite 6-ring windows sites. Thiophene approaches site.
- σ-donation of thiophene π-electrons to the 4s orbital of Cu(I) or Ni(II)
- d-π^* backdonation of electrons from 3d orbitals of Cu(I) or Ni(II) to π^* orbitals of thiophene

Sulfur Adsorber Prototype



- Three Sorbent Layers
  - Activated Carbon (12.4 wt%)
  - Activated Alumina (23 wt%)
  - Ni(II)-Y (64.6 wt%)
- Gasoline Rate: 50 mL/hr
- Equivalent H_2 Output: 2.8 moles/hr (100 W)
- Effluent Concentration: ~ 0.3 ppmw sulfur
- Operation Cycle: 9-10 hrs

Yang et al., U.S. and foreign patents applied.

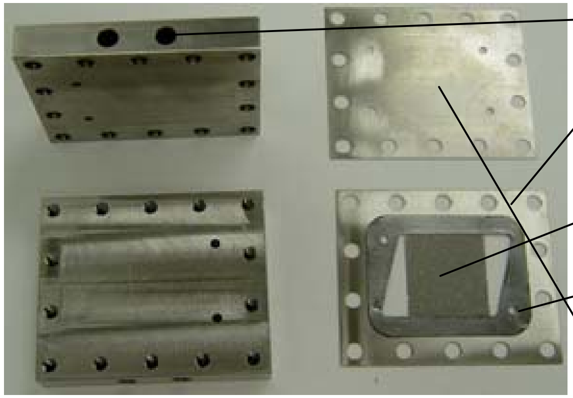
Microreactors

- Materials of Construction
  - Silicon Microfabrication
  - Micromachined Metals
  - Low Temperature Co-Fired Ceramics (LTCC)
- Metal Microreactors
  - 1st Generation (GEN1) Micro-reactor
    - Design and Fabrication
  - 2nd Generation (GEN2) Micro-reactor
    - Design Overview and Achievements
- Semi-solid Forming (SSF) Process

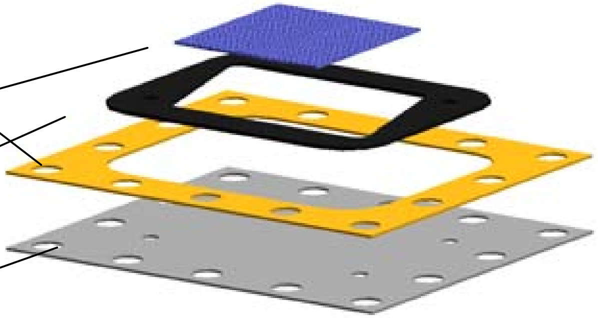
GEN2 Prototype Design

- Flexible design
- Assembled reactor module is 77 x 64 x 54 mm (25 stacks)

Assembled module

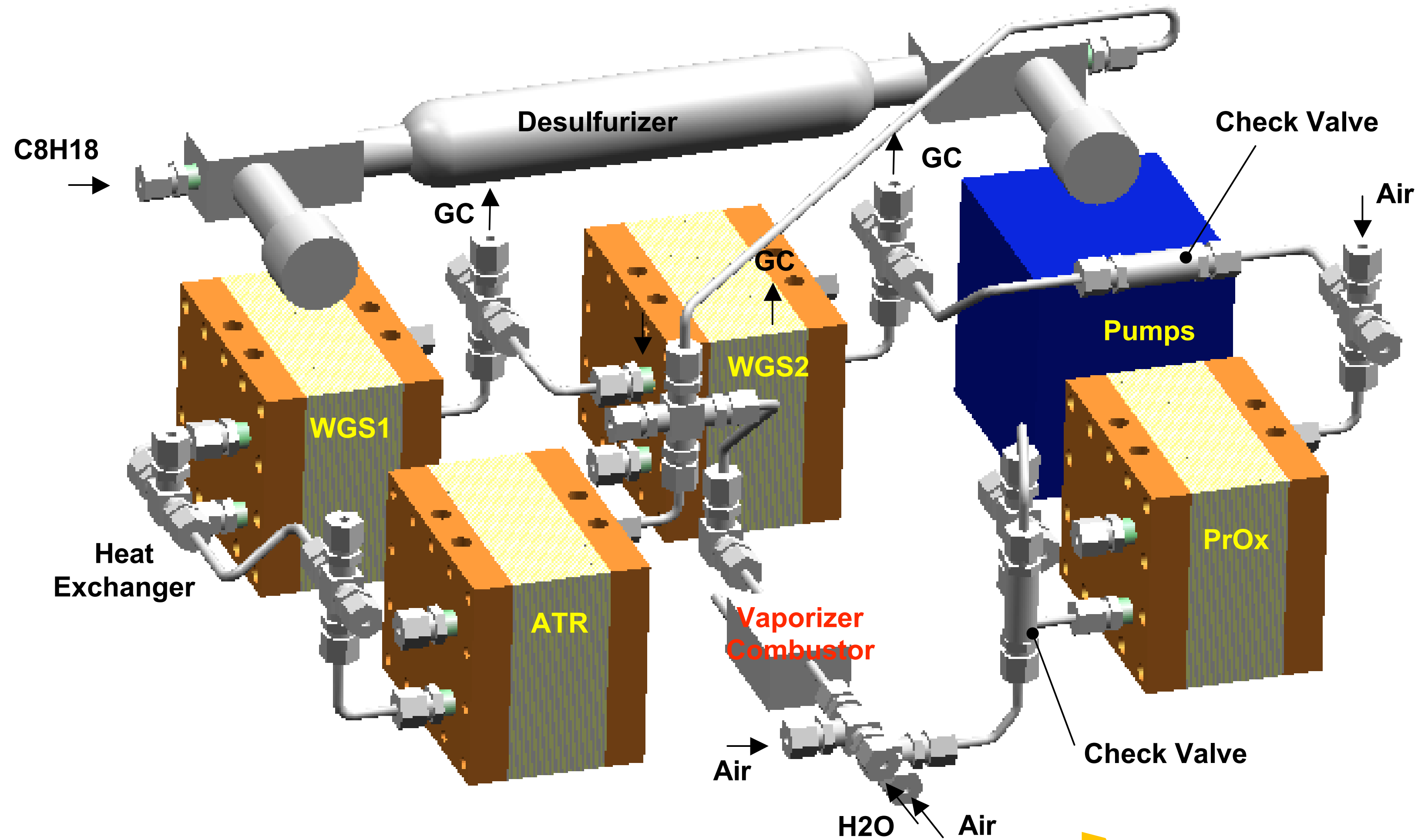


Fabricated Parts



Core Layers

Breadboard System



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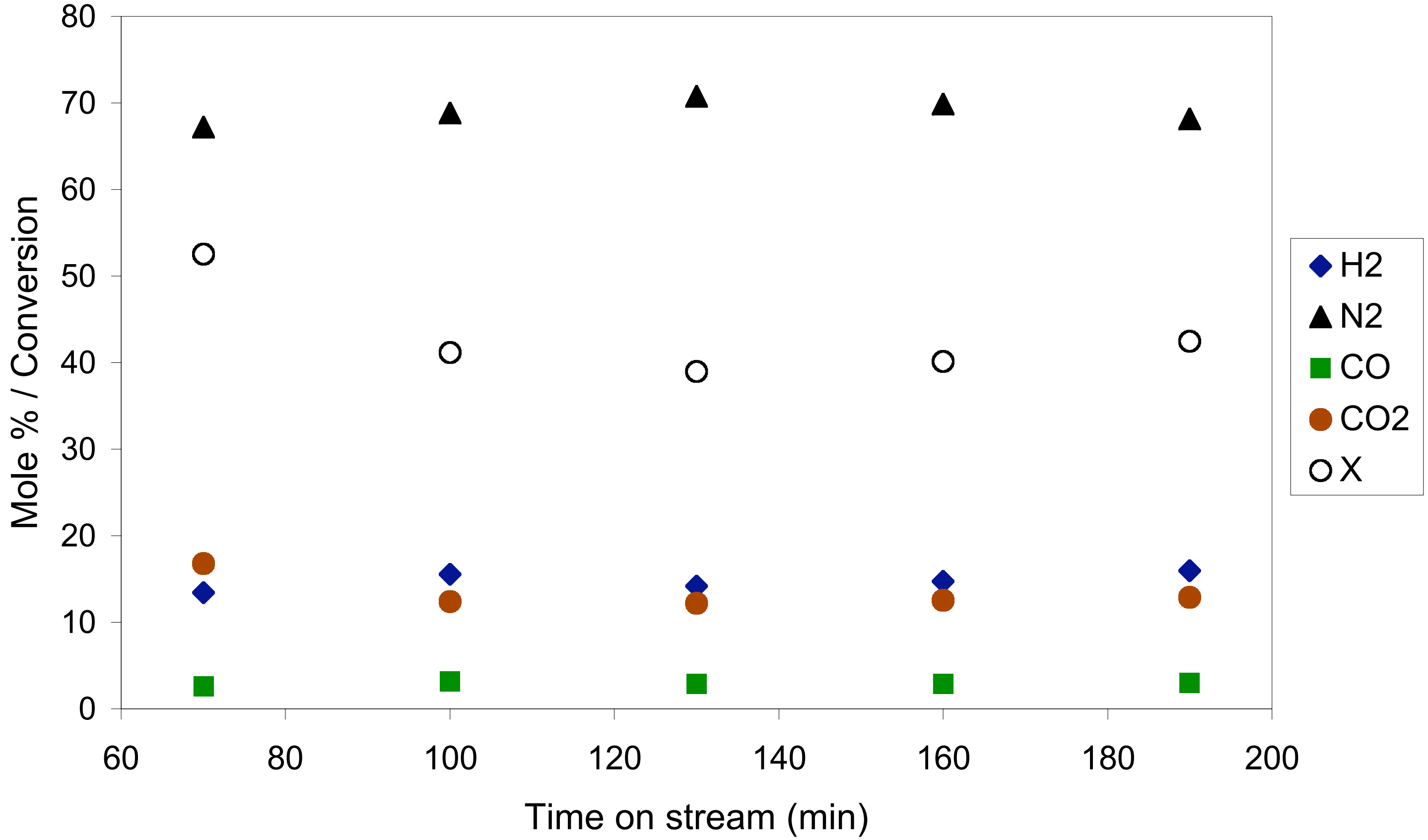
ATR Prototype Results (100 W_e)



Experimental Conditions: $H_2O/C = 2.0$, $O/C = 1.0$
Reactor Skin Temperature: 590 °C; Reactor Exit Temperature:385 °C
1.5 SLPM air, 0.6 mL/min Iso-octane, 1.1 mL/min H_2O

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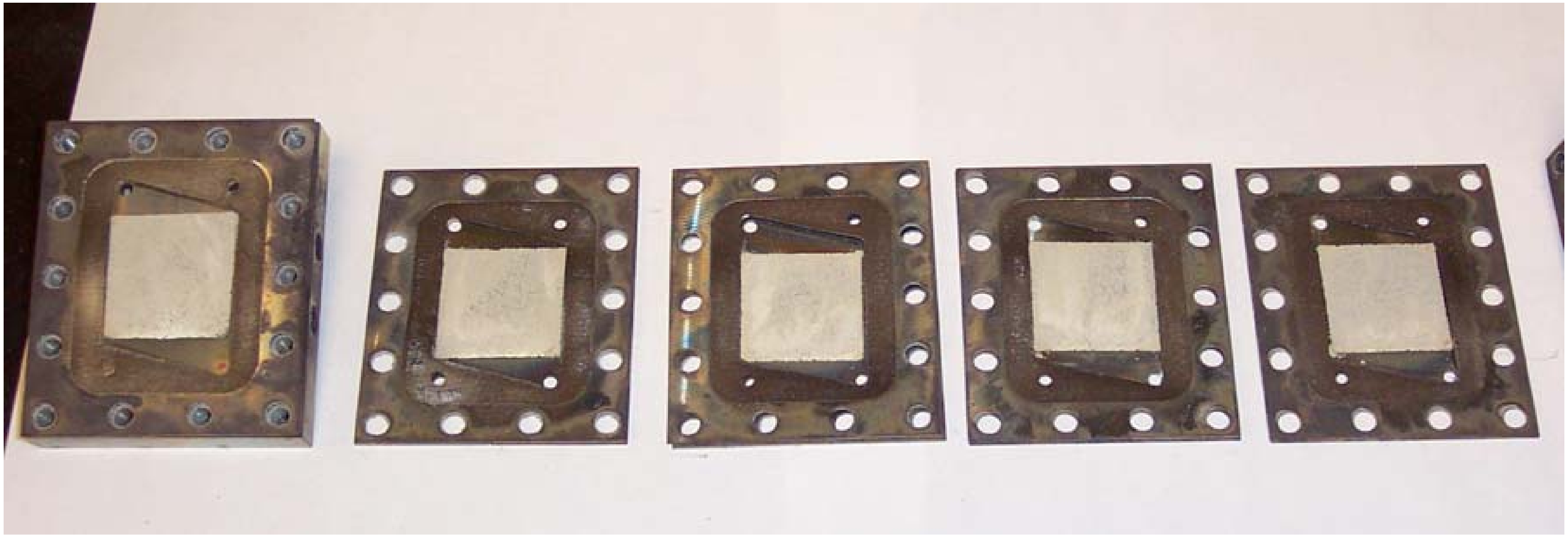
Minimal Coke Deposition



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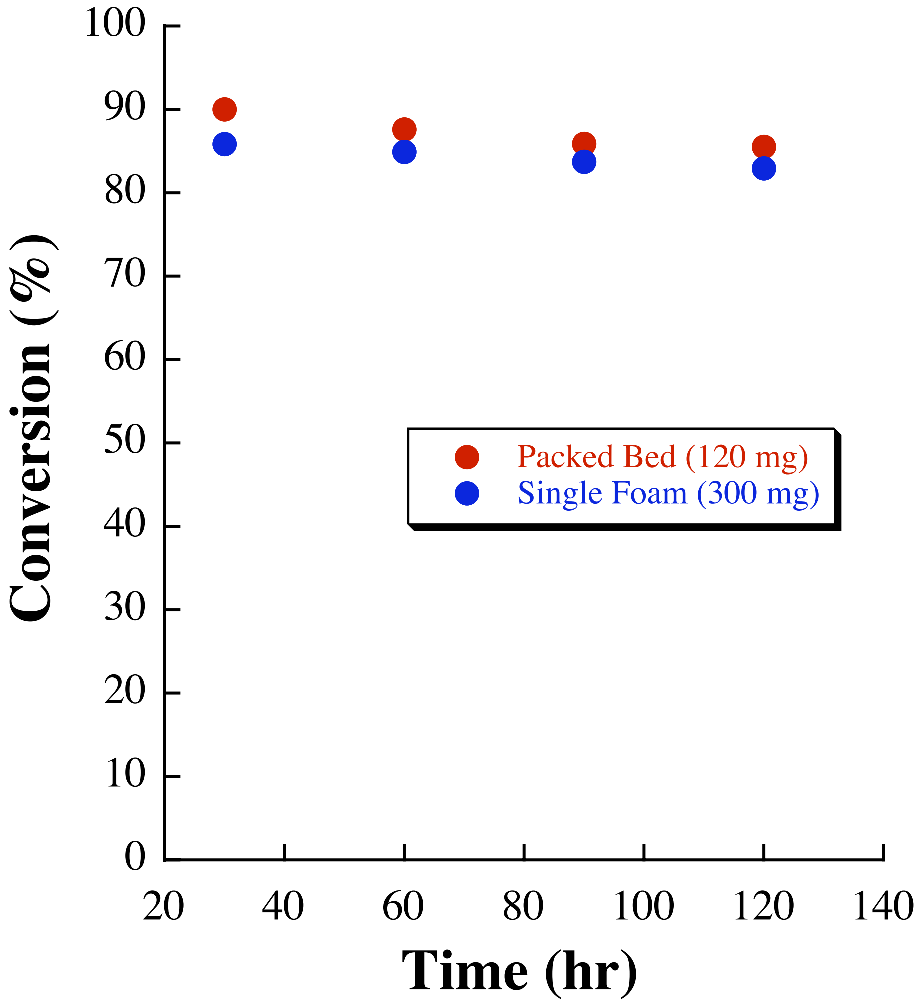
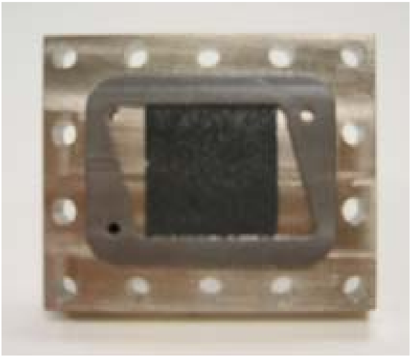
WGS Prototype Results



- Temperature: 240°C
- Flow rate: 40 ccm (1 W_e)
- GHSV: 53,333 h^{-1}
- Feed composition



CO	10%
H_2O	31%
CO_2	6%
H_2	39%
N_2	15%

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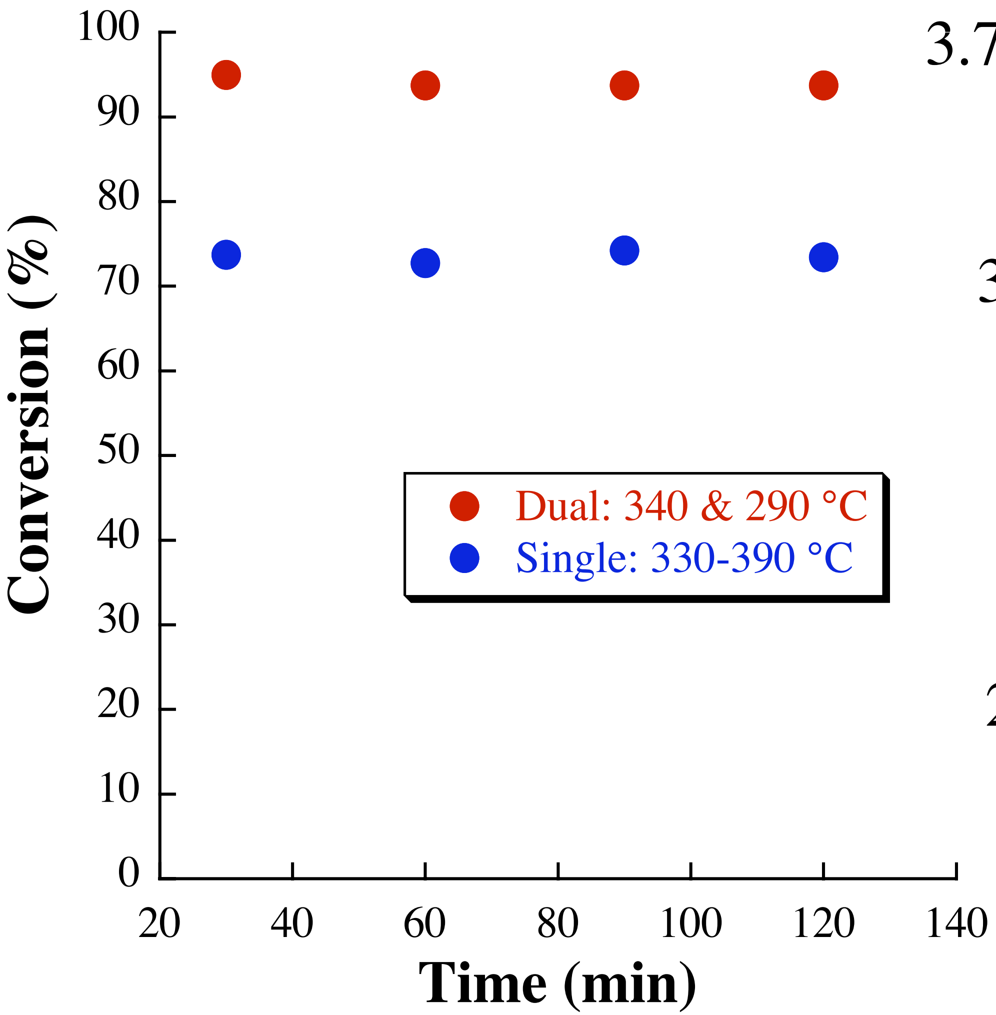
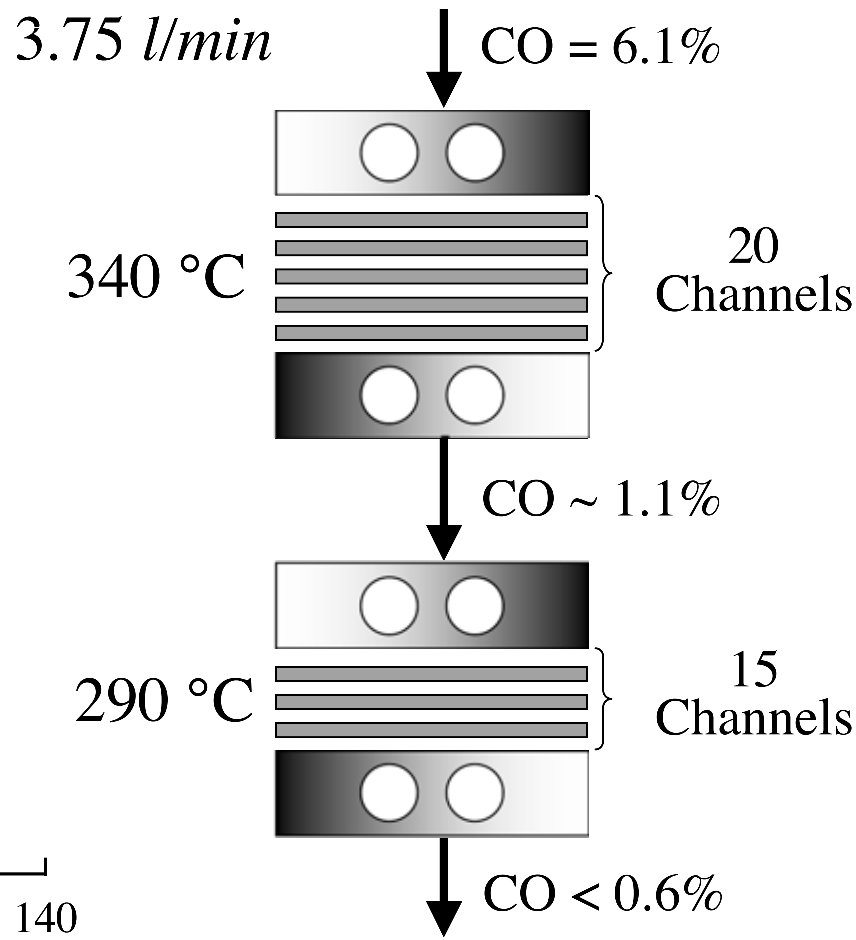
WGS Prototype Results ($100\ W_e$)





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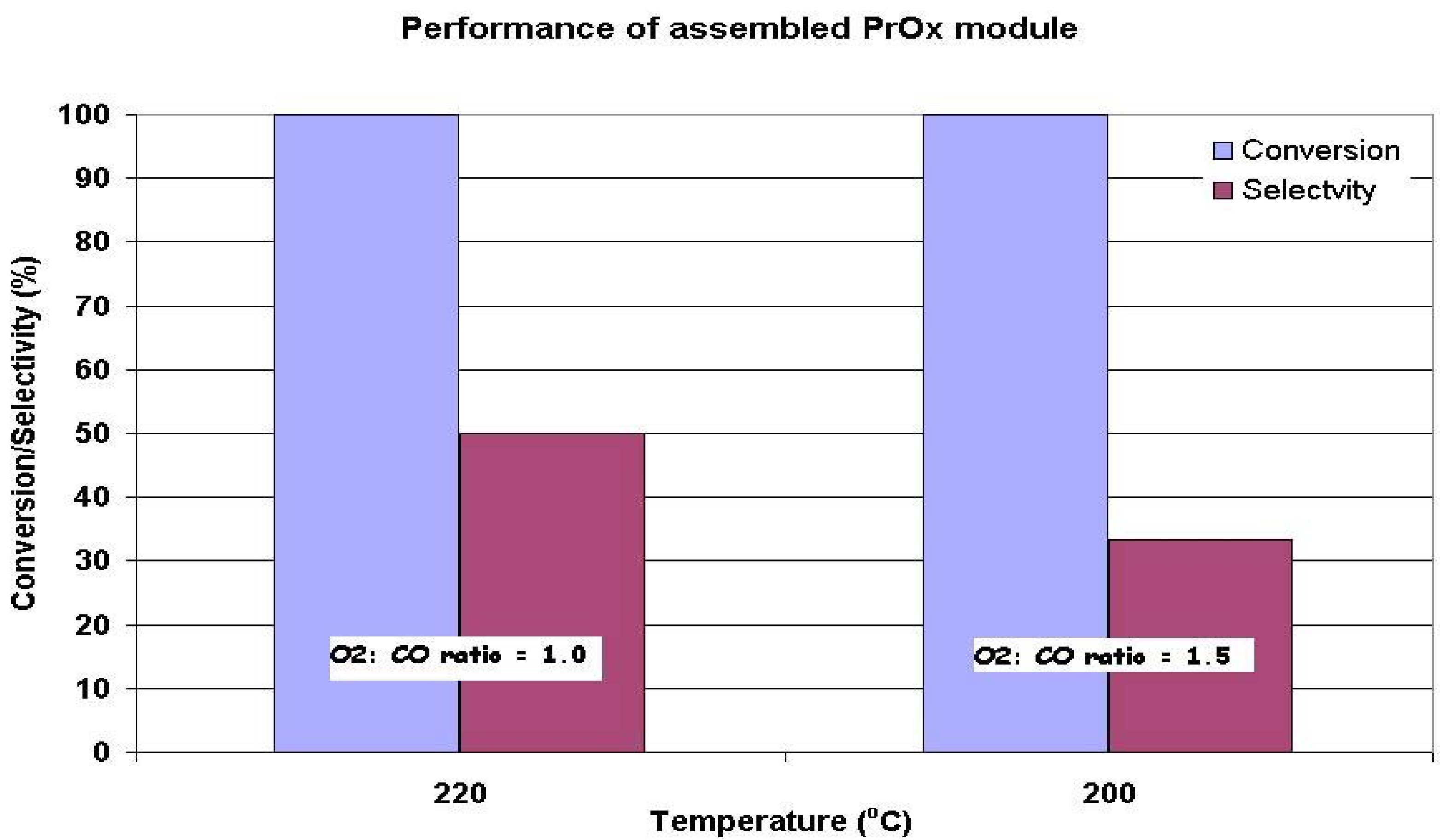
PrOx Prototype Results

- 4 % Pt-Al_2O_3 sol-slurry hybrid washcoat
- WHSV = 50 lit hr^{-1} g-cat^{-1}
- Increased catalyst loading of ~250 mg/foam
- Inlet stream compositions (simulated WGS exhaust):
  - CO : 0.79 – 0.81 %
  - O_2 : 0.81 – 1.19 %
  - CO_2 : 14.91 – 15.28 %
  - H_2 : 30.58 – 31.32 %
  - H_2O : 15.54 %
  - N_2 : 36.23 – 36.99 %

PrOx Prototype Results



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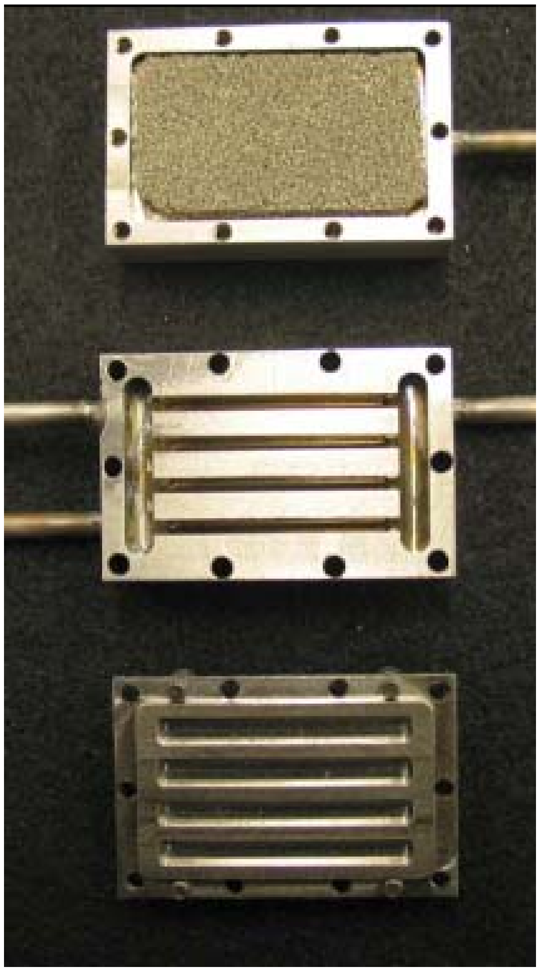
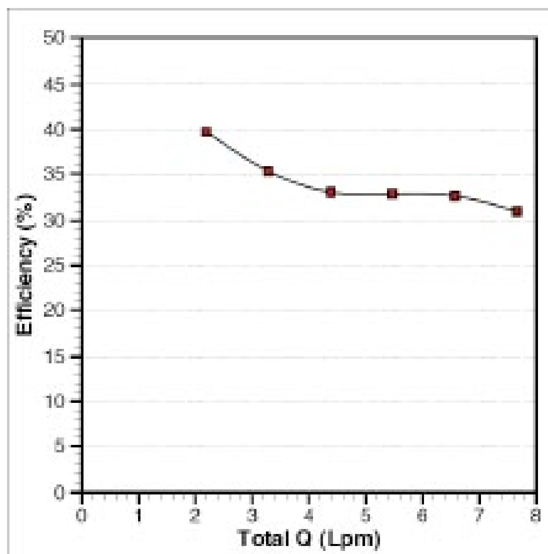
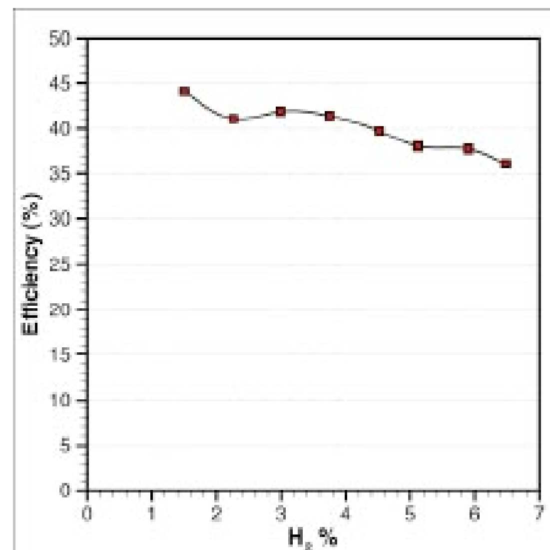
Catalytic Tailgas Combustor Prototype



Burner Characteristics:

- 100 W nominal capacity mesoscale burner
- 80 ppi Pt-coated FeCrAlloy metal foam
- 8.0 L/min tailgas low-H_2 surrogate flow rate





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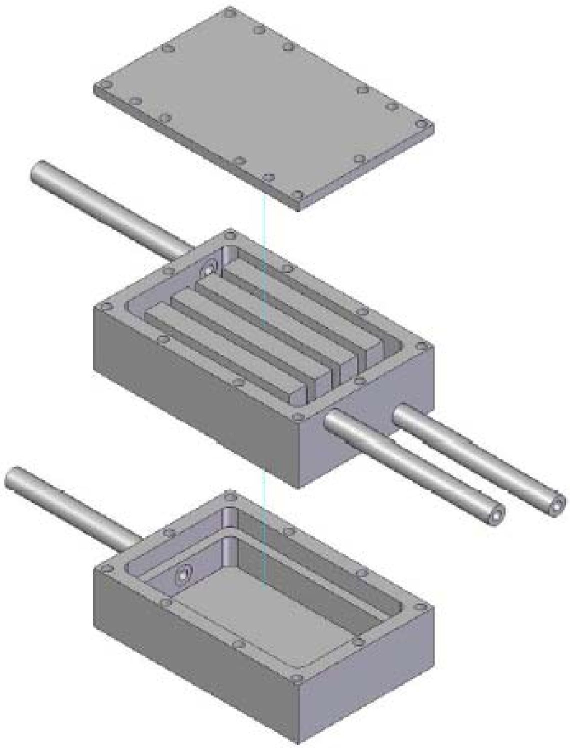
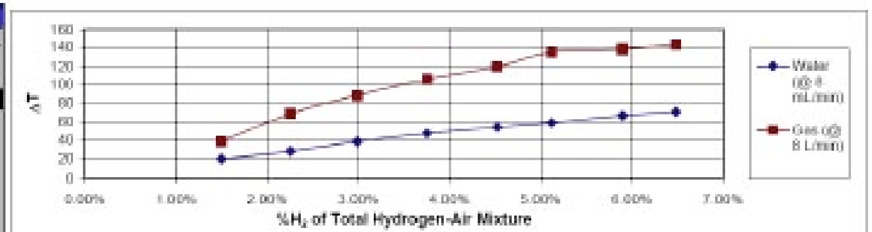
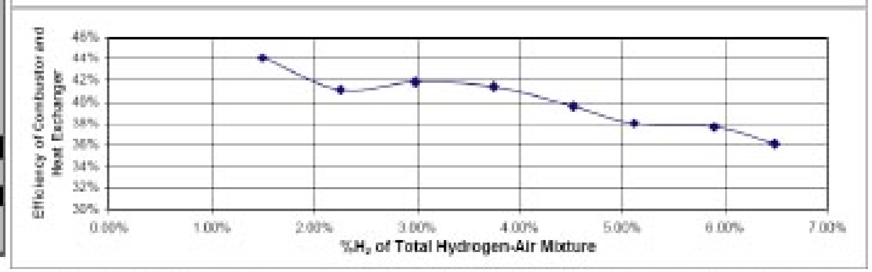
Catalytic Tailgas Burner and Heat Exchanger Prototype

- Performance tests conducted for 1.5% - 8% H_2 concentrations
- Current test results show single-sided efficiencies of 35-45%
- Double-sided efficiencies anticipated in 65-80% range



Constants		
Hydrogen Flammability Limits		
Φ_{min} =	0.14	
Φ_{max} =	2.54	
MW_{H2}	2.02	g/mole
MW_{Air}	29	g/mole
MW_{H2O}	18.02	g/mol
ρ_{H2}	0.0899	kg/m^3
ρ_{Air}	1.225	kg/m^3
ρ_{H2O}	993	kg/m^3
c_p of H_2O	4188.6	J/kgK
c_p of H_2	29.26	J/molK
	14485.15	J/kgK
c_p of Air	1500.00	J/kgK
LHV of H_2	140000	kJ/kg
Stoich	f_s =	34.17
Water Flow	8.0	mL/min
Rate	1.32E-04	kg/s





Φ	H_2 Flow	Air Flow	Total	H_2 %	q from H_2	Gas In	Gas Out	Gas ΔT	H_2O In	H_2O Out	H_2O ΔT	H_2O Δq	Gas Δq	q Lost	η
0.04	0.12	7.9	8.0	1.50%	25.2	304	342	38	302	322	20	11.1	1.5	13	44.1%
0.06	0.18	7.8	8.0	2.26%	37.8	304	373	69	302	330	28	15.5	5.4	17	41.1%
0.08	0.24	7.8	8.0	2.99%	50.3	304	392	88	302	340	38	21.1	6.6	23	41.9%
0.10	0.30	7.7	8.0	3.75%	62.9	306	412	106	302	349	47	26.1	7.3	30	41.4%
0.12	0.36	7.6	8.0	4.52%	75.5	307	427	120	301	355	54	29.9	7.0	39	39.7%
0.14	0.41	7.6	8.0	5.12%	86.0	308	443	135	302	361	59	32.7	8.0	45	38.0%
0.16	0.47	7.5	8.0	5.90%	98.6	308	446	138	302	369	67	37.2	5.2	56	37.7%
0.17	0.52	7.5	8.0	6.48%	109.1	308	451	143	303	374	71	39.4	3.8	66	36.1%
	Lpm	Lpm	Lpm		W	K	K	K	K	K	K	W	W	W	

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GEN2 100 W_e Prototype Design

	Vap/Com	ATR	WGS		PrOx
Temperature (°C)	450	600	340	290	220
Modules	1	1	1	1	1
Catalyst Type		$Ni/CeZrO_2$	Au/CeO_2	Au/CeO_2	Pt/Al_2O_3
Catalyst Weight (g)		1.5	6	4.5	2.4
No. of Foam cores		10	20	15	30
Foam Volume (cc)		4	8	6	12
Power Density (W/L)*					
Based on Foam	5,500	25,000	7,142		8,333
Target	5,882	10,417	2,525		9,091

Interactions and Collaborations

- Osram Sylvania (some IP transfer): Joel Christian - scale up of catalysts
- Ricardo: Marc Wiseman - system optimization and cost analysis
- Mesofuel: Doyle Miller - heat exchanger design and fabrication
- IMM: Volker Hessel - reactor design optimization

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Responses to Previous Year Reviewers' Comments

- Capacity of Cu(I) zeolite too low
- Coking of Ni-based ATR catalysts
- Verify performance of WGS catalysts
- Bottoms up approach
- Slow progress in developing microreactors
- Minimal involvement by companies
- Microprocessor work appears to be similar to PNNL
- Recommendations: Sulfur-tolerant ATR and hot gas sulfur sorbent

Future Work

- Remainder of FY03
  - Increase module power densities
    - Increase catalyst loading and utilization
    - Decrease parasitic weight (reactor and foam)
  - Assemble 100 W breadboard fuel processor
  - Evaluate cost and final size
  - Estimate start-up time
- FY04 (through end of 2004)
  - Demonstrate integrated module
  - Assemble 1 kW breadboard fuel processor

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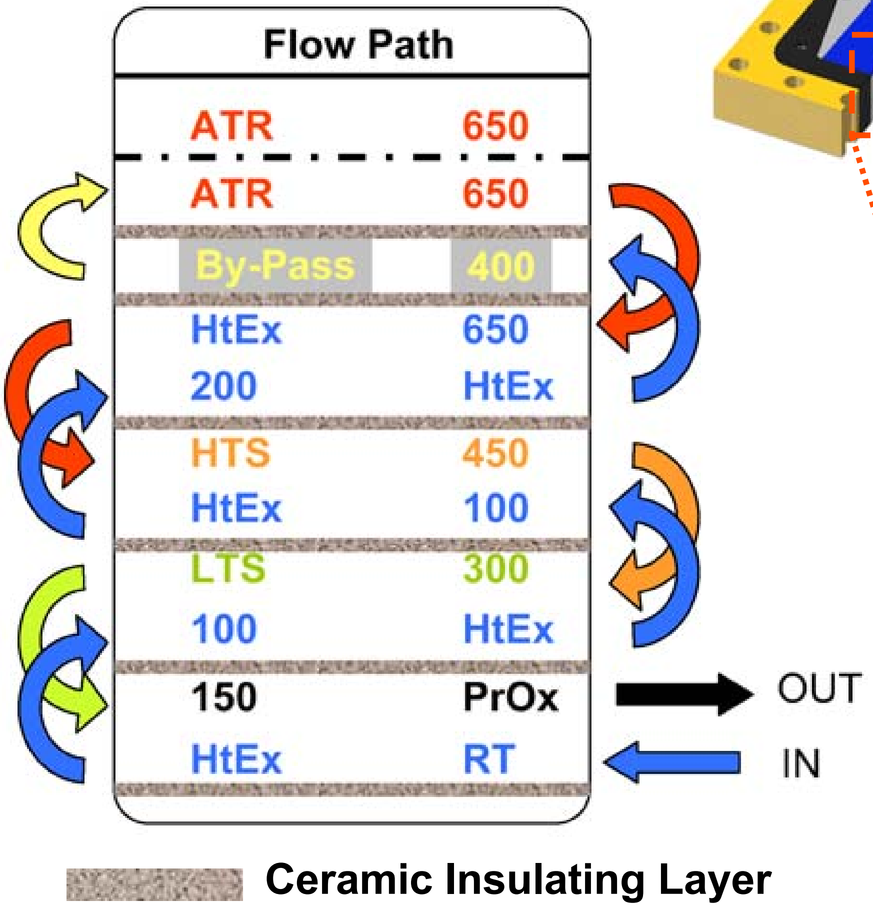
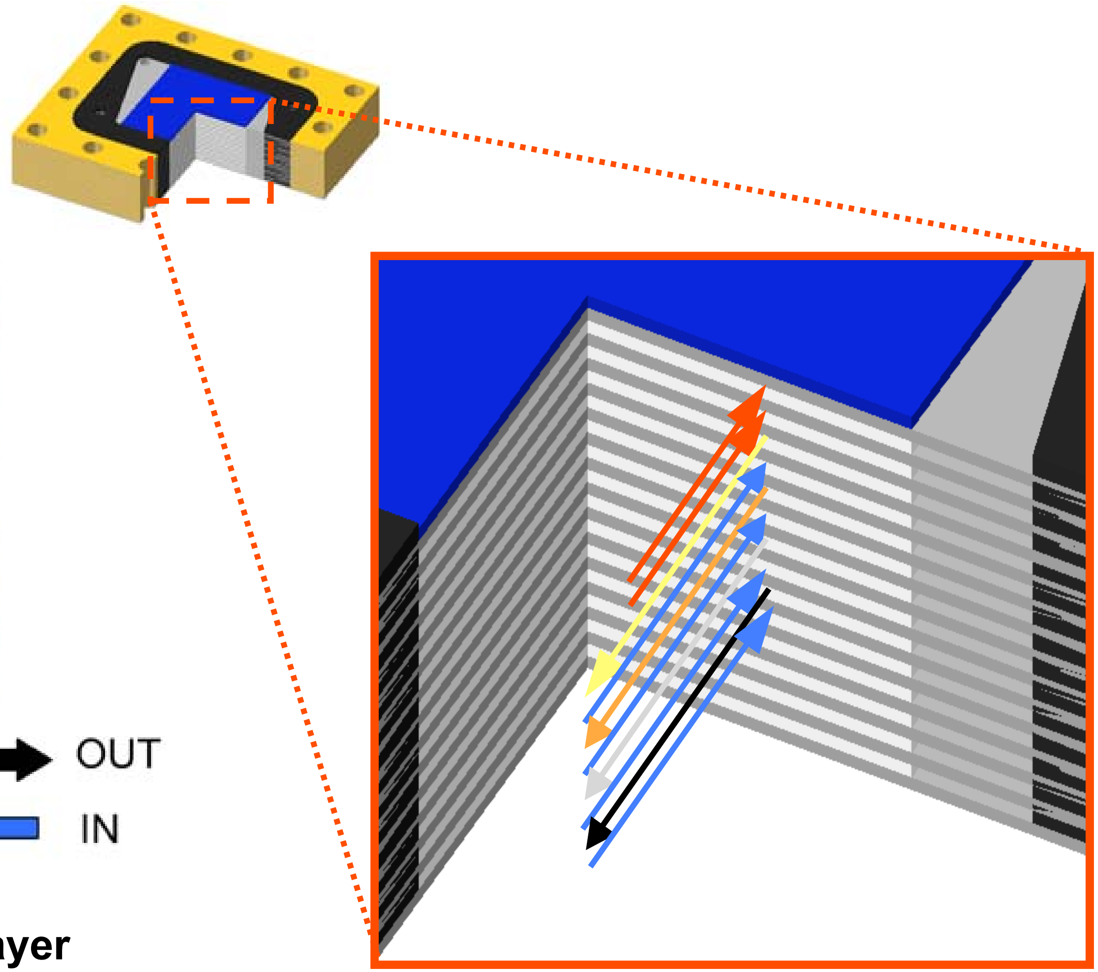
Stack Level Integration





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Thank You

High Performance Materials

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High Degree of Integration

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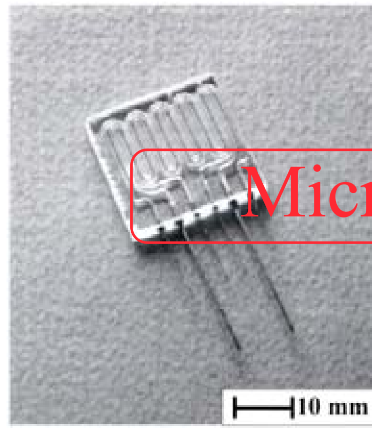
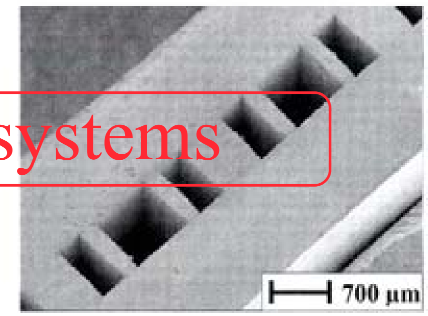


Microsystems



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